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Modular parametric analysis of satellite aerodynamic drag in LEO-VLEO

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Abstract

Aerodynamic drag remains a dominant source of uncertainty in satellite design for Low Earth Orbit (LEO) and Very Low Earth Orbit (VLEO), where rarefied gas dynamics and gas-surface interactions critically influence performance, lifetime, and mission planning. This work presents a modular, parametric, multi-fidelity analysis framework for quantifying drag sensitivity using a Radial Basis Function (RBF) surrogate model. The methodology is integrated into ESAT (EDL Sizing and Analysis Tool), combining automated geometry generation, simplified and high-fidelity aerodynamic solvers including DRIA or sparta DSMC, and atmospheric models ranging from USSA1976 to NRLMSISE-00, 2.0, or 2.1. The analysis accounts for geometric, aerodynamic, and environmental parameters, capturing the effect of orbital variability (e.g., latitude, solar activity) on drag. Figures of merit such as internal volume, surface areas, and inlet/outlet ratios are easily computed and monitored, and uncertainty in thermospheric properties is explicitly addressed through Monte Carlo simulations. The framework's modularity enables rapid trade studies across configurations and environments, with relevance for VLEO platforms operating in transitional and free molecular regimes. An application case based on a flat-panel, high aspect-ratio satellite illustrates the method's capability to guide early design decisions, including demisability and subsystem layout strategies. This approach supports the need for robust, design-time aerodynamic estimation tools for high-speed vehicles operating in the upper atmosphere, bridging engineering design and rarefied gas dynamics.

Keywords: *VLEO, drag sensitivity, MDO, MDA*

Nomenclature

AO – Atomic Oxygen
AP – Geomagnetic activity
AoA – Angle of Attack
AoS – Angle of sideslip
CAD – Computer Aided Design
Cd – Drag coefficient
Cl – Lift coefficient
DoE – Design of Experiments
DRIA – Diffuse Reflection with Incomplete Accommodation
DSMC – Direct Simulation Monte Carlo
EDL – Entry, Descent and Landing
ESAT – EDL Sizing and Analysis Tool
GSI – Gas Surface Interaction
HAR – High Aspect Ratio
HYDRA – Hypersonic Database & Real-time Aerodynamics
LEO – Low Earth Orbit
MDO – Multidisciplinary Optimization
MDA – Multidisciplinary Analysis
OML – Outer Mold Line
RBF – Radial Basis Function
SESAM – Semi-Empirical Satellite Accommodation Model
SPARTA – Stochastic PArallel Rarefied-gas Time accurate Analyzer
VLEO – Very Low Earth Orbit
α – Accommodation factor
T - Tesla
σ - Standard deviation
μ – micro (10^{-6})

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1. Introduction

Space operations are increasingly shifting towards Very Low Earth Orbits (VLEO), typically defined as altitudes between 100 km and 450 km [1]. Operating in VLEO offers distinct advantages, including enhanced imaging and sensing performance, which enable the use of smaller, more cost-effective platforms for applications such as Earth observation and communications [1], [**Error! Reference source not found.**], [3]. This growing interest has driven the development of technologies aimed at enabling sustained operations in this challenging environment [4].

The principal obstacle to long-duration VLEO missions is the presence of residual atmospheric gases, which generate significant aerodynamic drag on spacecraft, typically in the range of 1–100 mN/m². Compensating for this drag demands substantial on-board propellant, limiting mission lifetime and increasing operational costs. Two main approaches are pursued to address this issue: drag mitigation, through optimized spacecraft geometry and surface materials, and drag compensation, most commonly implemented via electric propulsion. Furthermore, the interaction between the rarefied VLEO atmosphere and spacecraft surfaces introduces additional design uncertainties, including aerodynamic forces, torques, and atomic oxygen-induced erosion, which are challenging to predict accurately.

Accurate prediction of aerodynamic drag remains one of the largest sources of uncertainty in both space operations and thermospheric science within LEO and VLEO [4], [5]. This challenge primarily stems from the difficulty of determining two interdependent parameters: atmospheric mass density (ρ) and the satellite drag coefficient (Cd). For example, density models derived from satellite observations inherently embed any drag coefficient errors as biases in density estimation. Thermospheric winds further contribute to uncertainty, representing a largely unmodelled and unpredictable force component. The VLEO environment is inherently dynamic, with neutral composition and ion concentrations exhibiting significant spatial and temporal variability driven by solar and geomagnetic activity, latitude, local time, and solar zenith angle. Atmospheric modelling has evolved from early empirical formulations of the 1960s, such as the 1976 Jacchia model, to more advanced frameworks like the NASA Goddard Mass Spectrometer and Incoherent Scatter (MSIS) series (MSIS-83, MSIS-86, MSISE-90), progressively expanding the range of modelled species and altitudes. The current state-of-the-art NRLMSIS-21 model provides global atmospheric characterization up to 1000 km altitude. Nevertheless, these models primarily resolve large-scale, slow-time variations, and may not fully capture high-frequency density fluctuations or atmospheric wave phenomena.

The drag coefficient itself is a complex parameter, influenced by gas-surface interactions (GSI), spacecraft geometry and attitude, relative velocity, atmospheric composition, local temperature, and surface properties. Of these, GSI is widely recognised as the most sensitive and influential factor in determining CD, and thus a key driver of drag prediction uncertainty.

1.1. Gas-Surface Interactions (GSI)

In VLEO, the atmosphere is highly rarefied, meaning the mean free path length of gas particles often exceeds the typical dimensions of a satellite. This classifies the flow regime as free molecular flow (FMF), where the forces and torques acting on a spacecraft are primarily the result of momentum and energy exchange between individual incident gas particles and the external surfaces.

GSI models characterize how incoming particles interact with the satellite surface and re-emit, influencing the level of energy and momentum accommodation. Two extreme types of reflection are differentiated, Fig 1 : Diffuse reflection, and specular reflection. With diffuse reflection, particles reflect according to a probabilistic velocity and direction distribution, losing much of the information about their initial energy and momentum. This is often the dominant behaviour in VLEO due to the adsorption of atomic oxygen (AO) on spacecraft surfaces [10], [6], [13]. With specular reflection, the angle of reflection equals the angle of incidence. The intermediate behaviour, where particles retain some information about their initial energy and momentum, is usually referred to as Quasi-specular reflection. The energy accommodation coefficient (α) is a key GSI parameter, representing the average fraction of energy lost by impinging molecules. It has been observed to be influenced by AO adsorption, as AO readily adsorbs onto satellite materials, modifying the inelasticity of collisions.

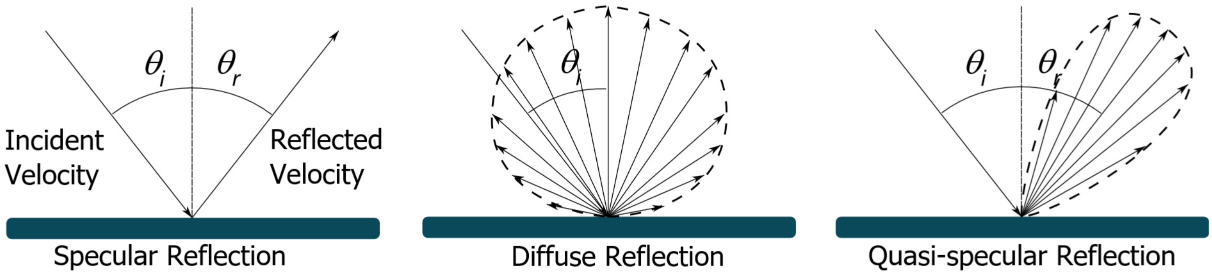

Fig 1. HYDRA reflection kernels

Empirical models, such as the Semi-Empirical Satellite Accommodation Model (SESAM), have been developed to predict accommodation coefficients across various solar activity levels and altitudes, based on the assumption that the fraction of surface covered by adsorbate is directly proportional to the accommodation coefficient.

1.2. Computational Methods for Drag Coefficient Estimation

Computational methods for estimating the drag coefficient of satellites range from analytical to fully numerical approaches. Analytical models, such as those by Sentman or Schaaf and Chambre, provide quick estimates for simple convex shapes like plates or spheres, but lose accuracy for complex geometries and at lower altitudes where non-linear flow effects become significant. Panel methods approximate the spacecraft by a collection of flat facets whose aerodynamic contributions are summed. Implementations such as ADBSat [4] allow general mesh import, flexible gas–surface interaction models, and limited shadowing analysis, offering speed for preliminary studies but reduced fidelity for concave geometries or cases with multiple reflections. Numerical approaches include Test Particle Monte Carlo (TPMC), which efficiently tracks particle-surface interactions under free-molecular conditions but cannot handle transitional flow, and Direct Simulation Monte Carlo (DSMC), pioneered by Bird, which models molecular motion and collisions in detail, capturing complex flow physics down to altitudes below ~200 km. DSMC tools such as SPARTA or NASA's DAC offer high accuracy but require significant computational resources. To balance accuracy and efficiency, hybrid approaches such as Response Surface Modelling with Gaussian Process Regression use numerical simulation data to train surrogate models capable of fast drag predictions have been also developed.

1.3. Current Research Efforts and Future Perspectives

Recent efforts aim to improve the accuracy and consistency of drag coefficient and density data sets, recognising that scale differences between thermospheric data sets largely originate from errors in aerodynamic modelling, particularly satellite geometry and GSI. Initiatives like the International Space Weather Action Teams (ISWAT) seek to establish a baseline for drag coefficient modelling consistency in science and operations.

Several missions and projects are dedicated to advancing the understanding of VLEO aerodynamics: Satellite for Orbital Aerodynamics Research (SOAR) is a 3U CubeSat mission designed to investigate GSIs of different materials in VLEO, providing in-situ characterization of aerodynamic performance at varying altitudes and incidence angles. Rarefied Orbital Aerodynamics Research (ROAR) facility is ground-based experimental facility at The University of Manchester, designed to reproduce the characteristic flux and energy of AO found in VLEO, providing crucial laboratory data for GSI characterization. High Accuracy Satellite Drag Model (HASDM), developed by the Air Force Space Battlelab, estimates and predicts a dynamically varying global density field by employing a dynamic calibration of atmosphere models.

Beyond improving general drag prediction, the detailed understanding of aerodynamic forces in VLEO enables novel mission concepts: differential drag, differential lift or shape optimization. The first intentionally varies the aerodynamic drag between spacecraft in a formation to control in-plane relative motion. The second uses aerodynamic lift to control out-of-plane motion, a concept gaining interest due to its potential for three-dimensional formation control. Shape Optimisation, on the other hand, aims to designing satellite geometries, such as biconical shapes or tapered tails, to minimize drag for lifetime extension or to enhance control authority for differential drag/lift applications [16].

The current state of the art highlights the critical need for a more comprehensive and integrated approach to satellite drag modelling. While significant advancements have been made in individual areas such as atmospheric modelling, CD computation, and GSI characterization, the interconnected nature of these uncertainties necessitates a holistic methodology. A modular parametric analysis, as proposed, is crucial to simultaneously address these uncertainties, leading to more accurate drag estimations and enabling the full potential of VLEO operations and propellant-less formation flight.

2. Drag sensitivity analysis framework with ESAT

The drag sensitivity analysis presented relies on ESAT (EDL Sizing and Analysis Tool), a tool developed within Indra-Deimos to support multi-disciplinary optimization (MDO) in complex aerospace design scenarios, Fig 2 . ESAT enables efficient exploration of design spaces by surrogate modelling techniques to approximate computationally expensive simulations.

At its core, ESAT uses Design of Experiments (DoE) techniques to run the analyses, seen as external black-boxes, in specific design points and interpolates the obtained responses with Gaussian Radial Basis Functions (RBFs). This tool has been successfully used by the Atmospheric Flight Competence Centre in Indra Deimos for diverse MDO tasks, including:

- Entry, descent and landing (EDL) system sizing for Mars and Titan missions [7].
- Sensitivity evaluation of a space launch vehicle, accounting for variations in stage-level parameters such as propellent mass, number of engines and nozzle expansion ratio [8], [9].

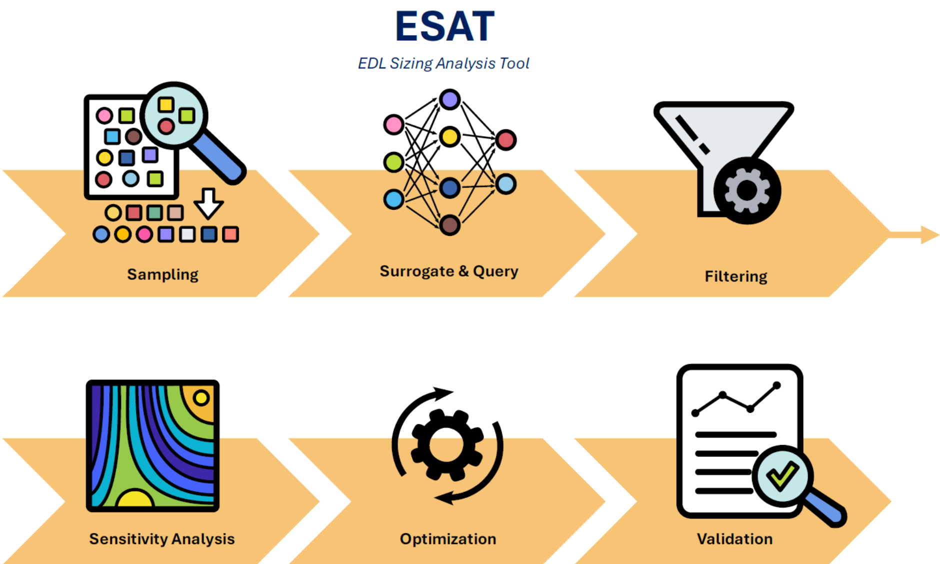

Fig 2. ESAT modules

2.1. ESAT workflow overview

ESAT's module architecture supports a structured workflow composed of the following stages: Sampling, Surrogate meta-model generation and query, filtering, sensitivity analysis, optimization and validation.

The process starts with sampling the design space using Latin Hypercube Sampling (LHS) to ensure a representative spread across the variable domain. At this stage, the user can connect multiple external modules to define the MDA. For the drag sensitivity analysis described in the current work, the following modules were integrated: geometry module, aerodynamic module, and postprocessing module.

The first one automatically generates geometry, exports the mesh and calculates geometric/inertial properties. Aerodynamic characterization leverages on geometry module's outputs, while post-processing module computes figures of merit and organizes the data for further steps, Fig 3.

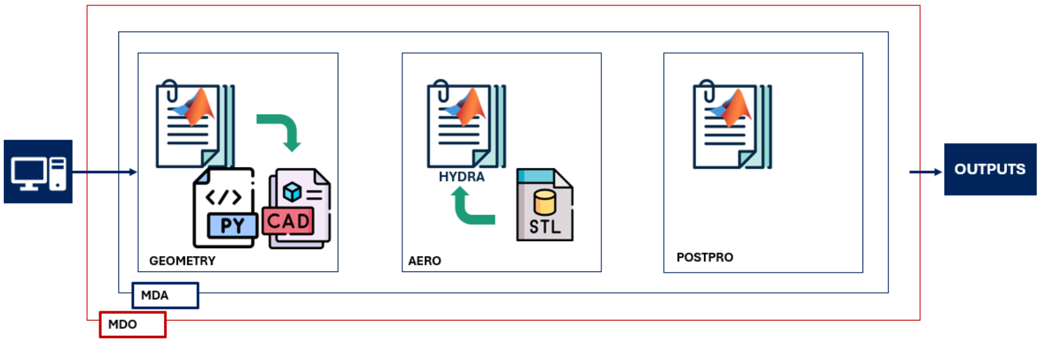

Fig 3. MDA external modules. CAD geometry generator, Aerodynamic and Postprocessing modules. Drag sensitivity analysis sampling

The modular, parametric approach of ESAT allows the analyst to customize as desired the formulation of the problem, so to tailor the fidelity of the models to the project phase.

In the MDA setup, it is key to define the design parameters that will populate the surrogate model. Also in this regard ESAT allows full flexibility, enabling the analyst to define parameters across multiple disciplines. Parameters can span through geometric variables (nose-cone angle, solar panel surface, satellite length, etc.), aerodynamic variables (angle of attack, angle of sideslip, reference area) or even environmental and operational conditions (accommodation factor, solar radiation, density, altitude, etc.). This flexibility shapes the surrogate model so to be capable of seizing the system behaviour across a wide and relevant design space, tailored to the specific objectives of the analysis.

Once the design space has been sampled and evaluated, ESAT, constructs a radial-based metamodel (RBF). The surrogate is then queried to interpolate and estimate responses across the entire design space, without re-running any expensive simulation.

To further focus on the analysis, the design space can be refined by applying filters to focus on regions of interest, based on specific performance metrics or constraints. The framework also includes a sensitivity analysis module, which generates correlation figures of input parameters over system outputs. The correlation plots allow the user to inspect parameters response relationships through domain slicing, helping identify key design drivers.

ESAT supports multi-objective optimization and identifies pareto fronts, aiding trade-off studies between competing design objectives.

Final step involves the validation of surrogate model predictions against a selected subset of original high-fidelity simulations. This provides metrics for metamodel accuracy and checks the reliability of optimized solutions.

While ESAT provides a robust framework for system-level analysis and optimizations, the quality and relevance of its outputs depend heavily on the fidelity and integration of the external modules it interfaces with. In this context, a significant portion of this document is dedicated to detailing the two main external modules used to perform the drag sensitivity analysis. The following sections describe the configuration, implementation and role of each external module in detail.

2.2. CAD generation module

The geometry generation process for the drag sensitivity analysis is built around SALOME, an open-source software that provides advanced tools for CAD modelling and mesh generation. Its modular interface and Python-base scripting make it suitable for integration into automated workflows, as an external module within ESAT.

Within ESAT framework, the CAD module is controlled through Python scripts that collects geometry-related design parameters as inputs (selected by the analyst according to the sensitivity and optimization goals of the analysis). Based on these parameters, SALOME script programmatically constructs the complete geometry starting by defining points, lines, surfaces and solid volumes. The module then proceeds to generate a computational mesh and extracts key geometric figures of merit (such as useful internal volume, frontal surface areas or specific features such as solar array surfaces). These outputs can directly be fed into performance evaluation criteria and optimization processes.

To control the dimensionality of the design space of ESAT and avoid excessive complexity, the geometrical model is intentionally simplified. This abstraction helps focus the analysis on specific design parameters while maintaining sufficient fidelity to capture the aerodynamic trends relevant to drag reduction.

2.3. Aerodynamic characterization module

The aerodynamic module relies on an Indra Deimos proprietary aerodynamic tool, HYDRA [**Error! Reference source not found.**]. The Hypersonic Database & Real-time Aerodynamics, referred to as HYDRA, is a module for the preliminary assessment of the hypersonic and Free Molecular Flow (FMF) aerodynamics on the aero-shape Outer Mold Line (OML). It focuses on the precise definition, implementation, and analysis of a modified Newton method tailored specifically for hypersonic aerodynamics. The core objective of HYDRA is to enable rapid computation of vehicle aerodynamics, utilizing a program written in the C programming language.

HYDRA is modular, and multiple aerodynamic methods (e.g. Straight Newton, Modified Newton, Modified Non-Calorically Perfect Newton, Viscous Modification, FMF, Sentman, DRIA) are implemented. Particularly the DRIA as Gas-Surface Interaction method is selected in the current study.

Gas-Surface Interaction models are crucial in understanding the forces and torques acting on satellites in the thermosphere, particularly in the Very Low Earth Orbit (VLEO) regime. In this rarefied environment, the atmosphere behaves like a collection of particles, and the interaction of these gas particles with the satellite's surfaces determines the momentum and energy exchange, ultimately influencing the satellite's drag and lift. Consequently, accurate GSI modelling is essential for precise satellite orbit determination. Residual inconsistencies observed between different thermosphere data sets and between data and models often originate from the complexities in GSI modelling [10], [11], [12], [13], [14].

Two fundamental types of scattering mechanisms are typically considered in GSI models: specular reflection, where particles reflect at an equal angle to the incident angle, and diffuse reflection, where particles are reflected according to a probabilistic distribution of velocity and direction. Various models exist to describe these interactions, including Maxwell's model, which combines specular and diffuse reflection, and the Cercignani-Lampis-Lord (CLL) model, which provides a more sophisticated description using scattering kernels for normal and tangential velocities, or Diffuse Reflection with Incomplete Accommodation (DRIA).

DRIA is a specific type of GSI model that assumes the gas particles are reflected diffusely from the satellite's surface, but with incomplete energy and/or momentum accommodation. This means that the reflected particles are not necessarily in complete thermal equilibrium with the surface they interacted with. A key aspect of many DRIA models is the consideration of atomic oxygen adsorption onto the satellite surface, particularly at lower thermosphere altitudes where atomic oxygen is a dominant species. The hypothesis is that the presence of adsorbed atomic oxygen significantly influences the gas-surface interactions and thus the accommodation coefficient (α), which quantifies the degree of energy exchange between the incident gas particles and the surface.

Early DRIA models, such as those developed by Pilinski et al. [11] often employed a Langmuir isotherm to relate the inferred accommodation coefficient to the partial pressure of atomic oxygen, assuming a diffuse reflection kernel. These models attempt to infer the value of α by fitting drag coefficients of satellites with relatively simple shapes to observational data. The DRIA model has shown success in reproducing fitted CD at lower altitudes, where the adsorption of atomic oxygen is thought to be significant.

2.4. Environment

The environment definition is a critical component of the drag sensitivity analysis framework, particularly for missions operating in VLEO, where atmospheric interaction significantly impacts the satellite performance and lifetime. This section outlines the environmental modelling that can be integrated within ESAT framework. At a high level, ESAT allows for the specification of orbital and atmospheric parameters that influence aerodynamic behaviour, including: Altitude, temperature and orbital geometry, Atmospheric composition and density profiles, Solar activity indicators, such as the F10.7 solar flux index, Geomagnetic disturbances, described by AP indices, Accommodation factor, inclusion of Monte Carlo assessments to account for orbital parameter's variability, including cross-track and down-track deviations.

Environmental settings define the external conditions under which the aerodynamic characterization is evaluated, significantly impacting the accuracy of both surrogate modelling and sensitivity analysis. The ESAT tool is compatible with empirical atmospheric models such as NRLMSISE-00, 20, and 21 [15] which is used to enable altitude and time dependent density estimation based on solar and geomagnetic activity inputs.

3. An application example: VLEO HAR satellite

Over the recent years, there has been a marker rise in the deployment of small satellites with flat-panel geometries book-like, driven primarily by the needs of large-scale low earth observation constellations such as Starlink and OneWeb. These satellites feature flattened, rectangular structures that allow for dense launch packing, low-drag configurations, and efficient power generation via body-mounted solar arrays. Their scalability, manufacturability and suitability for low-altitude operations have made a standard for modern commercial space applications.

In this context, the following application case illustrates the use of ESAT to perform a drag sensitivity analysis for a representative satellite design inspired by this geometry class. The goal is to assess how variations in geometry parameters affect the drag performance within a very-low earth orbit (VLEO) environment. The case integrates the CAD, aerodynamic and postprocessing modules described earlier, showcasing how the modular architecture of ESAT enables a preliminary and rapid exploration of design sensitivities and supports data-driven optimizations within the early design-steps of a project.

3.1. Environment modelling

For the presented drag sensitivity analysis, the environmental conditions are set up to simulate a representative and conservative VLEO scenario. A circular orbit at 230 km altitude and 70º inclination was selected, corresponding to a common configuration for earth observation missions, Fig 4.

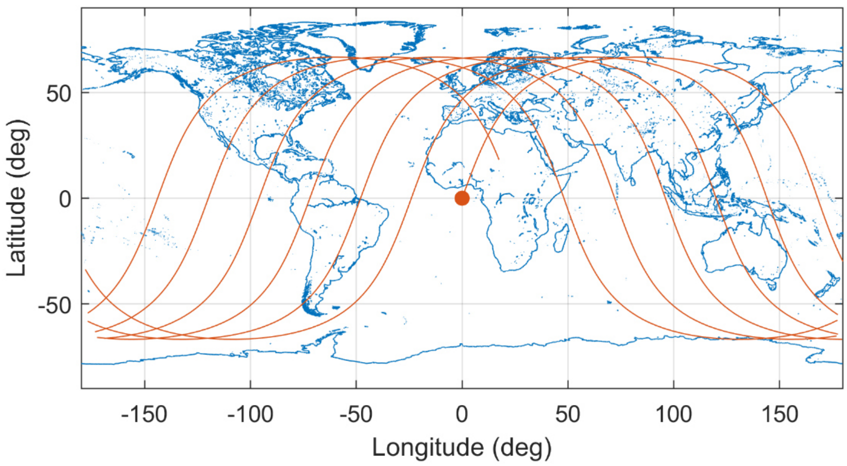

Fig 4. Orbital propagation

To account for atmospheric density variability, a Monte Carlo simulation of 20000 shots was performed. Each shot simulates a potential scenario along the orbit, sampled across latitude and seasonal distributions and providing statistical insight into the range of total atmospheric densities the satellite may experience.

Atmospheric data is driven by the NRLMSISE-00 model, with parameters adjusted to reflect a worst case with high solar activity scenario. By analyzing historical trends of solar flux (F10.7) and geomagnetic activity (AP) a 5σ condition is selected, which represents an extremely active but possible operational environment.

Fig 5 shows the latitude-dependent density variability derived from the Monte Carlo analysis. Seasonal shifts due to solstices and equinoxes are also reflected in the density range.

Table 1. Environmental, solar activity parameters

Variable	***Value***	***Unit***	***Description***
nShots	20000	-	Number of shots considered
Jd0	01/03/2032	-	Julian Date to start the propagation
altitude	230	Km	Orbit geocentric altitude
Inclination	70	º	Orbit inclination
V_inf	7.7665e+03	m/s	Orbital velocity
Acc	0.95	-	Accommodation factor
F10.7	358.5	sfu	Solar Flux
AP	112	$2\mu \cdot T$	Geomagnetic activity index

Fig 6 shows the NRLMSISE-00 composition profile by number of densities as a function of altitude. At the target altitude of 230 km atmosphere is primarily composed by atomic oxygen (O) and molecular nitrogen (N2). Fig 7 highlight the historical evolution of the F10.7 flux and AP, with the selected 5σ condition adopted for the worst-case scenario.

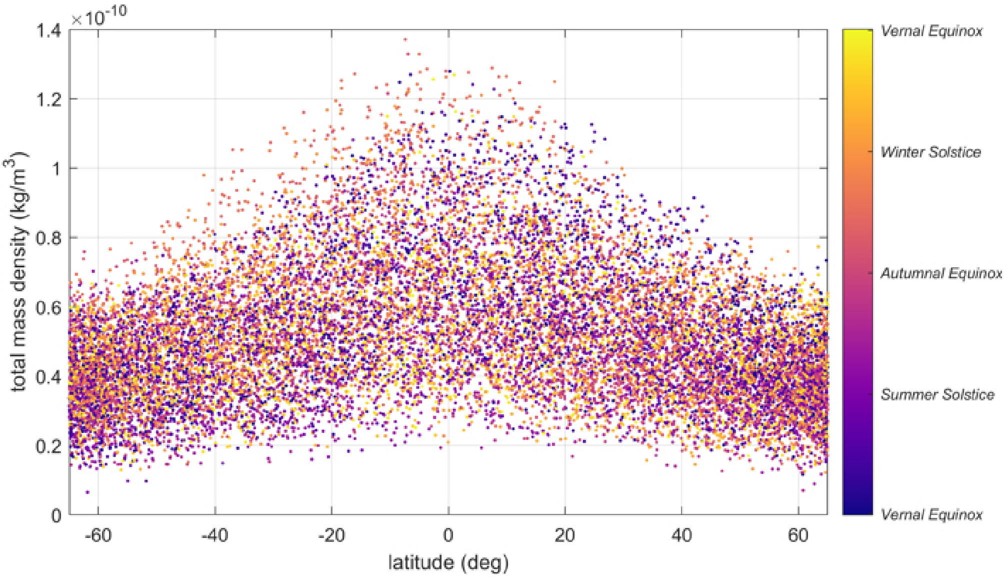

Fig 5. Monte Carlo total mass density

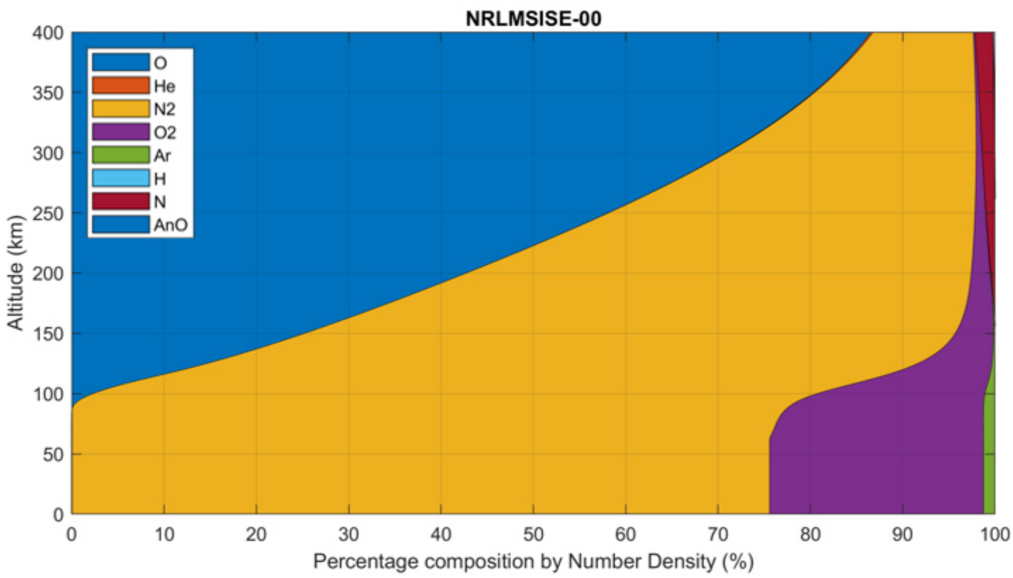

Fig 6. Percentage composition by number density

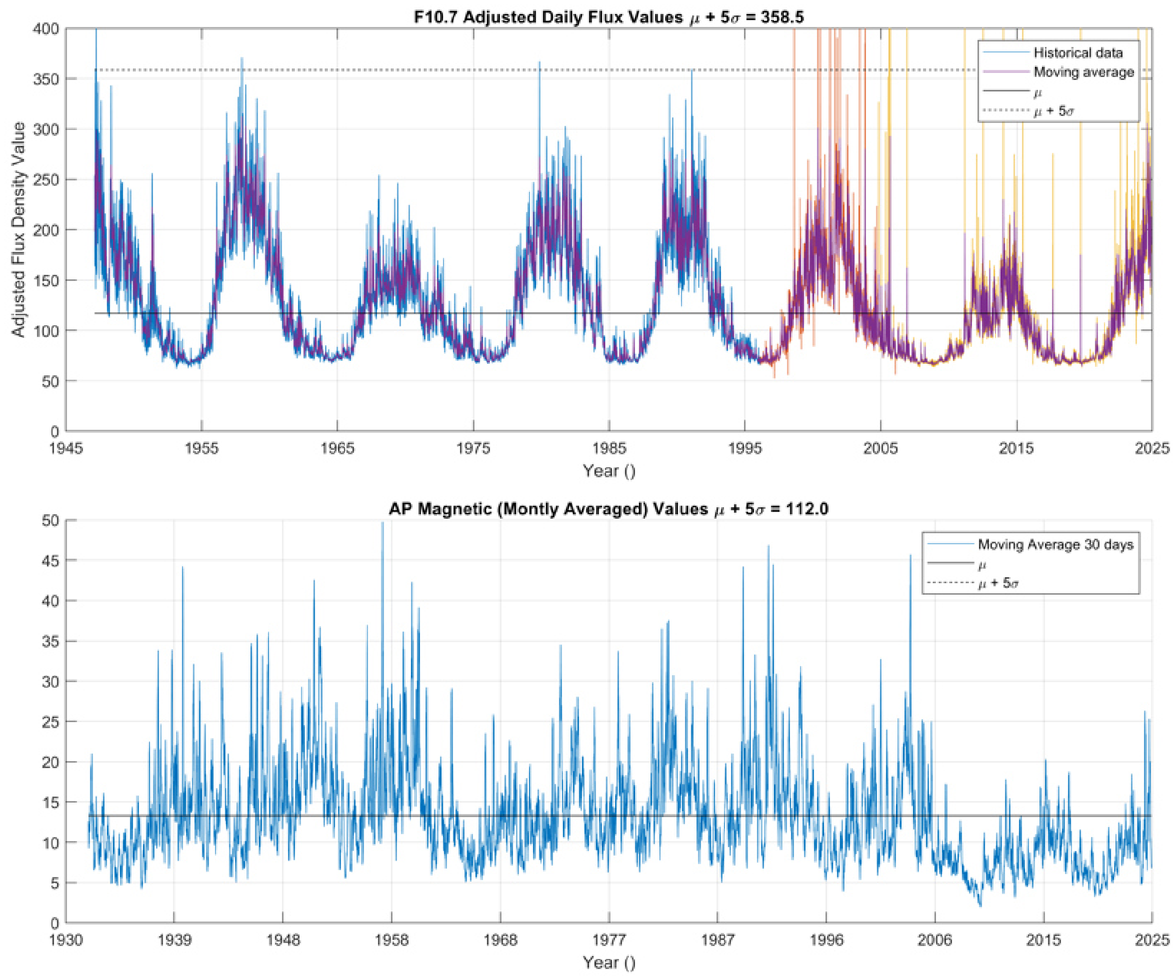

Fig 7. F10.7 solar flux (above) and AP geo-magnetic index historical measurements (below)

3.2. Geometry and sampling

As a case of study, a high aspect ratio satellite geometry is presented. The configuration is geometrically defined by four control points, each located within a 2D plane, and treated as design parameters. These points are assigned variability ranges that are sampled by ESAT during the construction of the surrogate model. While the overall thickness/height of the satellite remains fixed to focus the analysis, the control points modulate features such as lengths, slopes and curvatures, allowing for the generation of multiple shape variants within the same family architecture. The parametric variation directly influences different figures of merit that can be monitored throughout the analysis, including inlet and outlet surface areas, top surface area and internal volume.

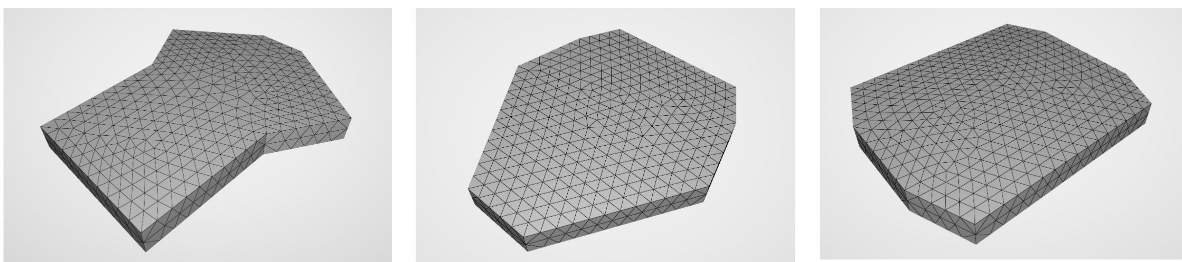

Fig 8. Samples generation examples

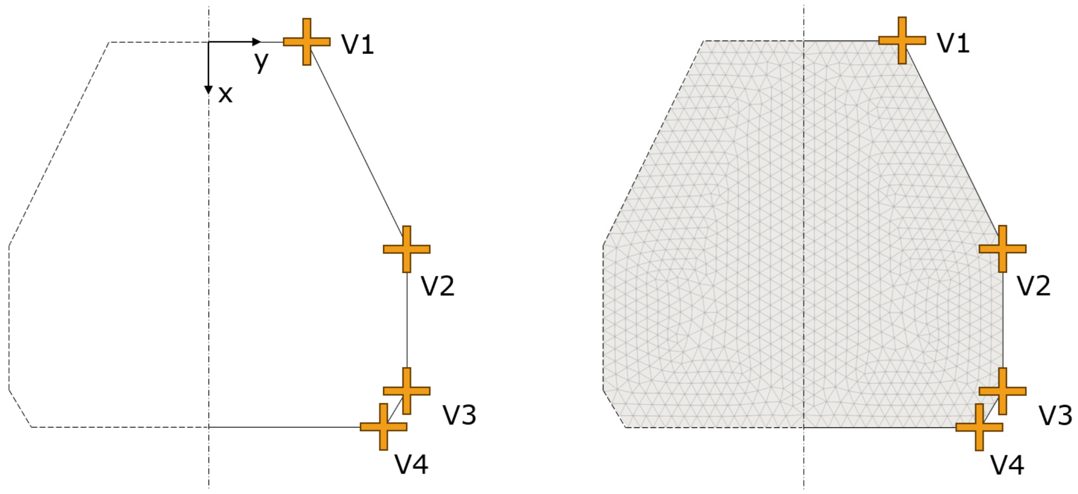

Fig 9. Geometry example definition. Generation points and mesh definition.

To generate the surrogate model, a set of 1000 samples was generated across the defined design space. This sample set ensures a well-distributed representation of geometrical configurations, enabling accurate metamodel construction prediction and performance evaluation.

3.3. Aerodynamics

To characterize the aerodynamic performance of the satellite geometry across the design space, HYDRA was employed with specific Free Molecular Flow model. Gas-surface interaction was represented using diffuse reflection with incomplete accommodation model, which captures the diffuse scattering behaviour of the impinging molecules over the satellite surfaces.

The aerodynamic figures of merit extracted from the analysis include the drag coefficient (C_D), lift coefficient (C_L) and the decommissioning drag coefficient, that corresponds to the drag at an angle of attack of 90º, used as a proxy for decommission conditions. These coefficients were computed for each sample within the surrogate model across a sweep of orientations, enabling performance characterization over the design space.

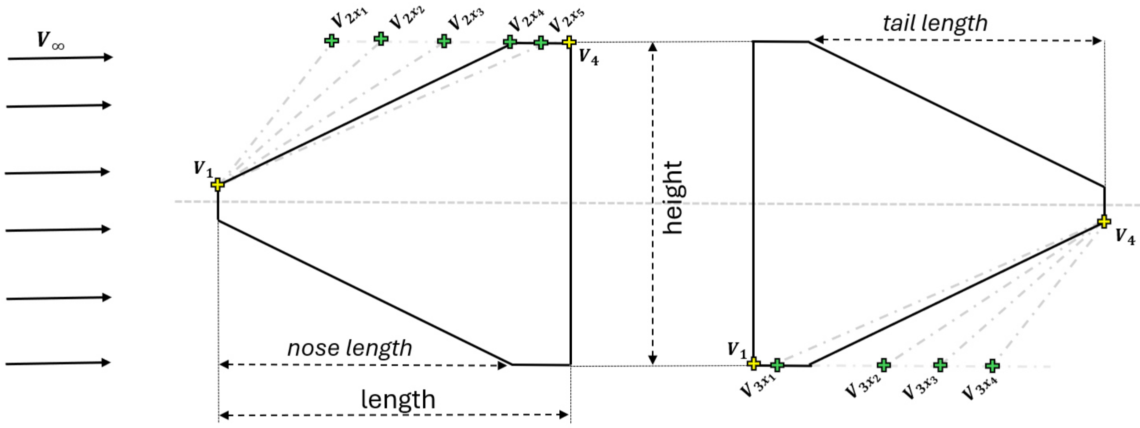

Fig 10. Geometry of simulated satellite, showing key areas of variation

The methodology also enables assessment of deviations from the nominal operating conditions. To estimate the impact of potential guidance and control errors, the aerodynamic module evaluates a grid of points centred on the nominal flight condition (i.e. $\alpha = 0º$, $\beta = 0º$). From this, the mean and standard deviation of C_D and C_L are computed, quantifying sensitivity to small attitude perturbations and providing a measure of robustness under operational uncertainties.

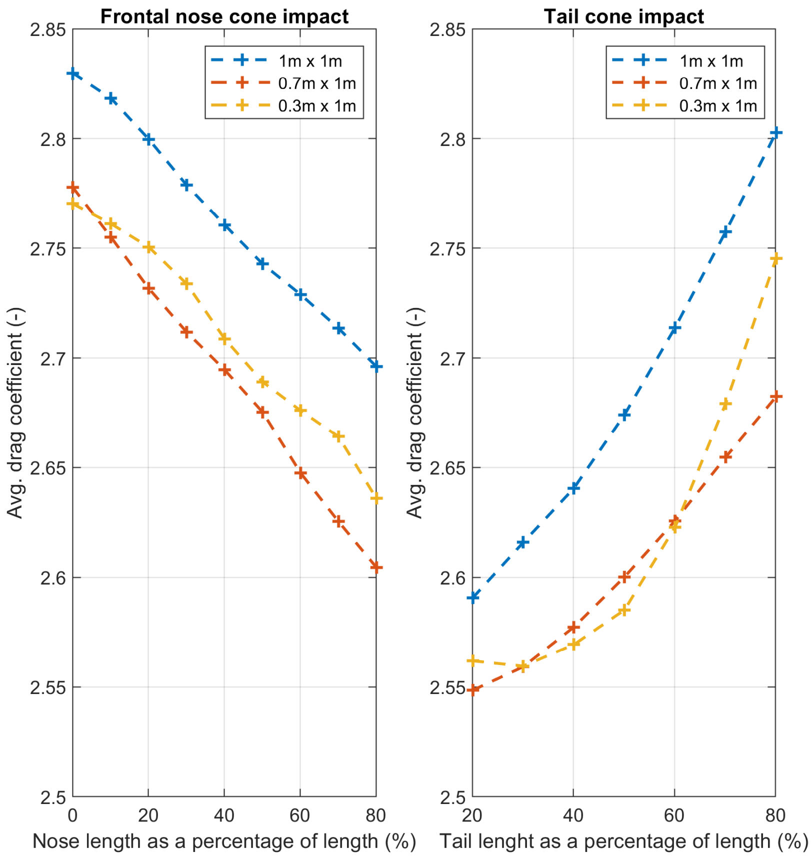

Fig 11. Drag element analysis. Impact of nose and tail length with fixed satellite width.

3.4. Sensitivity analysis

A key outcome of the workflow is the ability to perform design sensitivity analysis, which quantifies the influence of design parameters on performance metrics. Once the surrogate model is constructed, ESAT enables efficient querying across the design space and reveals how variations in geometry affect system-level behaviour without requiring additional high-fidelity simulations.

Fig 12 illustrates one of the sensitivity results extracted for the application case, where the variability range of four geometric figures of merit (Inlet surface area, outlet surface area, top surface area and satellite volume) are overlaid against the drag coefficient as a function of the angle of attack. These variability bands illustrate the span of drag coefficient associated with geometric changes at different vehicle attitudes, for a single representative case within the surrogate model. While this shot proves insight into how variations in individual geometric features influence drag locally, it does not fully represent the variability across the entire design space. Statistically robust conclusions are then drawn from the global sensitivity analysis performed on the full set of samples, where trends and parameter impacts are derived from aggregated surrogate evaluations across the sample geometrical configurations.

4. Conclusions and way forward

This paper presents the application of the ESAT framework to analyse the aerodynamic behaviour and preliminary design assessment of a small satellite operating in a very low earth orbit environment. By combining a parametric geometry definition with a structured sampling process, a surrogate model was generated to explore the relationships between geometry and aerodynamic performance, across a wide range of flight conditions. The key strength of the ESAT architecture lies within its fast, flexible, multi-fidelity capability. This allows for flexible and consistent integration of tools across different modelling fidelities. As an example, the possibility to choose among Panel methods or Numerical methods (e.g. SPARTA DSMC solver), enables to tune each module’s fidelity as required by the design phase of the project. Similar considerations can be made for the environment module, that can leverage upon:

USSA1976, NRLMSISE-00, 20, or 21. Trade-offs between computational efficiency and physical accuracy, are crucial to adapt to the needs of each study.

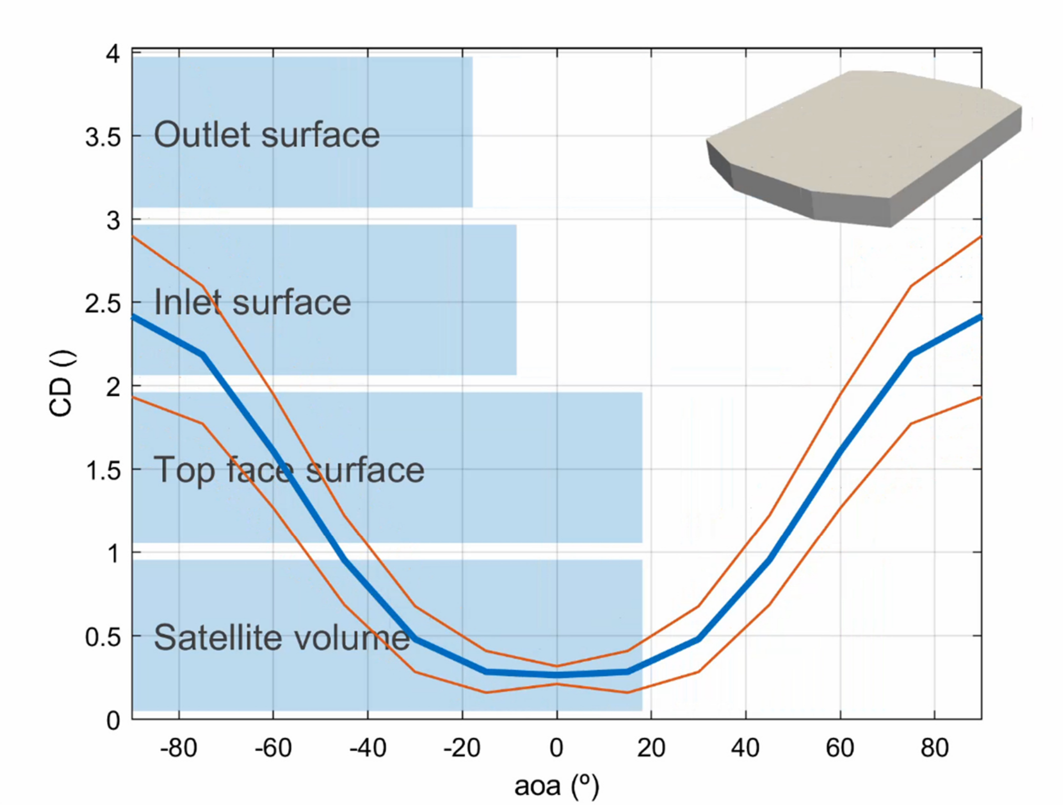

Fig 12. Sensitivity analysis of the Drag coefficient to outlet, inlet and outlet surfaces and useful satellite volume.

Key figures of merit such as drag coefficient, lift coefficient and decommission drag value were extracted. To assess the robustness against attitude uncertainty, additional evaluations were performed around the nominal flight condition, allowing for the estimation of potential performance variability due to navigation or control errors. The geometry sensitivity analysis offers valuable insights into how specific features (such as internal usable volume, front cone shape and tail configuration) can influence the aerodynamic behaviour of the satellite. Although these findings are specific to the selected case, they highlight the ESAT capabilities to support the early stages of the satellite design, providing insight into a wide range of possible parameters (geometric, environmental, etc.)

Looking forward, thanks to the ESAT flexible framework, higher fidelity modelling of the geometry module can be integrated. For example, by defining components volumes budget, their internal location can be parametrized as well. This will enable to compute the expected mass, inertia tensor and centre of gravity, paving the way for mass budgeting, centre of gravity optimization and ballistic coefficient computations. The interdependence between aerodynamics and inertia can be also assessed by integrating a flying qualities module. Similar considerations apply to the power budget that could be easily linked to the solar array surfaces figure of merit. These additions would allow pushing even further the satellite design optimization during early conceptual design phase.

References

1. Andreussi, Tommaso, Eugenio Ferrato, and Vittorio Giannetti. "A Review of Air-Breathing Electric Propulsion: From Mission Studies to Technology Verification." *Journal of Electric Propulsion* 1, no. 1 (2022): 31. https://doi.org/10.1007/s44205-022-00024-9
2. Crisp, Nicholas H., Peter C. E. Roberts, Sabrina Livadiotti, Alejandro Macario Rojas, Vitor Toshiyuki Abrao Oiko, Steve Edmondson, Sarah Haigh, Brandon Holmes, Luciana Sinpetru, Katherine Smith, et al. "In-Orbit Aerodynamic Coefficient Measurements Using SOAR (Satellite

for Orbital Aerodynamics Research)." *Acta Astronautica* 180 (2021): 24–35. https://doi.org/10.1016/j.actaastro.2020.12.024

3. Crisp, Nicholas H., Peter C. E. Roberts, Virginia Hanessian, Valeria Sulliotti-Linner, Georg H. Herdrich, Daniel Garcia-Alminana, Dhiren Kataria, and Simon Seminari. "A Method for the Experimental Characterisation of Novel Drag-Reducing Materials for Very Low Earth Orbits Using the Satellite for Orbital Aerodynamics Research (SOAR) Mission." *CEAS Space Journal* 14, no. 4 (2022): 655–674. https://doi.org/10.1007/s12567-022-00434-3

4. Mostaza-Prieto, David. *Characterisation and Applications of Aerodynamic Torques on Satellites*. PhD thesis, University of Manchester, 2017. https://research.manchester.ac.uk/en/studentTheses/characterisation-and-applications-of-aerodynamic-torques-on-satel

5. Mehta, Piyush M., Smriti N. Paul, Nicholas H. Crisp, Philip L. Sheridan, Christian Siemes, Günther March, and Sean Bruinsma. "Satellite Drag Coefficient Modeling for Thermosphere Science and Mission Operations." *Advances in Space Research* 72, no. 12 (2022): 5443–5459. https://doi.org/10.1016/j.asr.2022.05.064

6. Marianowski, Claudia, Constantin Traub, Marcel Pfeiffer, Julian Beyer, and Stefanos Fasoulas. "Satellite Design Optimization for Differential Lift and Drag Applications." *CEAS Space Journal* 17, no. 1 (2024): 11–29. https://doi.org/10.1007/s12567-024-00550-2

7. F. Toso, G. De Zaiacomo, A. Rivero, A. Princi, G. Medici, I. Oprea. 2024. "Advancements in Mission Engineering for Space Rider". In: 75th International Astronautical Congress, Milan, Italy, 14-18 October 2024

8. F. Toso, G. Medici, J. Gudagnini, G. de Zaiacomo. 2024. "Multidisciplinary Analysis Framework for the Mission Design of Reusable and Space Transportation Re-Entry Vehicles". HiSST: 3rd International Conference on High-Speed Vehicle Science Technology

9. Medici G., Ionita A., De Zaiacomo G., Bonetti D., et. al. 2017. *"Multi-Disciplinary Optimisation of Re-entry Vehicles from TAEM to Landing."* 2017. Paper presented at the 7th European Conference for Aerospace Sciences (EUCASS 2017), Milan, Italy, July 2017. In *EUCASS 2017 Conference Proceedings*. https://doi.org/10.13009/EUCASS2017-413

10. Pilinski, M. D. 2011. Dynamic Gas Surface Interaction Modeling for Satellite Aerodynamics. University of Colorado

11. Pilinski, Marcin D., Brian M. Argrow, and Scott E. Palo. 2010. "Semiempirical Model for Satellite Energy-Accommodation Coefficients." *Journal of Spacecraft and Rockets* 47 (6): 951–956. https://doi.org/10.2514/1.49330

12. Pilinski, Marcin D., R. L. McNally, B. A. Bowman, S. E. Palo, J. M. Forbes, B. L. Davis, R. G. Moore, K. Kemble, C. Koehler, and B. Sanders. 2016. "Comparative Analysis of Satellite Aerodynamics and Its Application to Space-Object Identification. " *Journal of Spacecraft and Rockets* 53 (5): 876–886. https://doi.org/10.2514/1.A33482

13. Traub, Constantin, Georg H. Herdrich, and Stefanos Fasoulas. 2020. "Influence of Energy Accommodation on a Robust Spacecraft Rendezvous Maneuver Using Differential Aerodynamic Forces." *CEAS Space Journal* 12: 43–63. https://doi.org/10.1007/s12567-019-00258-8

14. Mehta, Piyush M., Smriti N. Paul, Nicholas H. Crisp, Philip L. Sheridan, Christian Siemes, Günther March, and Sean Bruinsma. 2022. "Satellite Drag Coefficient Modeling for Thermosphere Science and Mission Operations." *Advances in Space Research* 72 (12): 5443–5459. https://doi.org/10.1016/j.asr.2022.05.064

15. Picone, J. M., A. E. Hedin, D. P. Drob, and A. C. Aikin. 2002. "NRLMSISE-00 Empirical Model of the Atmosphere: Statistical Comparisons and Scientific Issues." *Journal of Geophysical Research: Space Physics* 107 (A12): 1468. https://doi.org/10.1029/2002JA009430

16. Jonathan Walsh, Lucy Berthoud, Christian Allen – Drag reduction through shape optimisation for satellites in Very Low Earth Orbit - 2021